

BEAM-PLASMA EFFECTS IN MUON IONIZATION COOLING LATTICES*

J. Ellison, P. Snopok, Illinois Institute of Technology, Chicago, IL 60616, USA

Abstract

New computational tools are essential for accurate modeling and simulation of the next generation of muon based accelerator experiments. One of the crucial physics processes specific to muon accelerators that has not yet been implemented in any current simulation code is beam induced plasma effect in liquid, solid, and gaseous absorbers. We report here on the progress of developing the required simulation tools and applying them to study the properties of plasma and its effects on the beam in muon ionization cooling channels.

INTRODUCTION

Though muon accelerator simulation codes have been steadily improving over the years, there is still much room for improvement. Many single-particle processes and collective effects in vacuum and matter, such as space charge, beam-beam effects, plasma effects from ionized electrons and ions, etc. have not been studied thoroughly or implemented. In order to ensure proper accuracy of simulations, these effects have to be either deemed negligible or taken into account.

Ionization cooling is a method by which the overall emittance of a muon beam can be reduced. A beam is sent through a material, losing momentum as they ionize electrons, and reducing its overall emittance. By reaccelerating the beam through RF cavities, the longitudinal momentum is restored and any lost energy is regained (Fig. 1).

Muons will ionize material as they travel through absorbers. This can generate a plasma, and it is the interaction of the muon beam with the generated plasma that is studied here. Beam-plasma interaction is not taken into account currently in a majority of muon accelerator simulation codes. This can be needed when simulating ionization cooling and high-pressure gas-filled RF (HPRF) cavities.

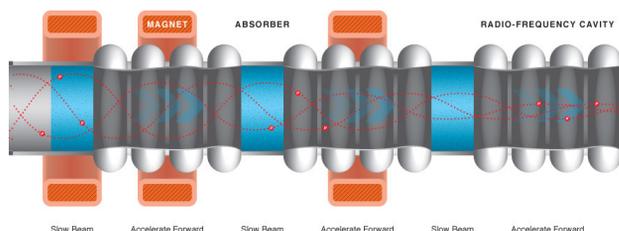


Figure 1: A diagram of ionization cooling. In each cell, absorbers reduce the transverse and longitudinal momentum of the muon beam, and RF cavities reaccelerate in the longitudinal direction only, reducing the overall emittance of the beam.

* Work supported by the U.S. Department of Energy.

The plasma effects have been studied by plasma physicists, but has not been studied extensively from a beam physics point of view. The plasma has been shown to not disrupt the beam or make it blow up [1]. For ionization cooling purposes, beam-plasma effects may have a large impact on the cooling rates for both charges of muon. Essentially, the head of a bunch sees a material with different properties than the tail of the bunch. Ionization rates vary from material to material so the effects may be more prominent in some materials than others.

QUALITATIVE SIMULATIONS

After several simulation packages were considered, the one found to best suit our needs was WARP [2]. WARP is an extensively developed particle in cell (PIC) simulation code designed to simulate charged particle beams with high space-charge intensity. A dense Gaussian beam of muons ($N = 10^{12}$, $p = 200$ MeV/c) was sent through a solenoidal magnetic field ($B = 5.46$ T) and Hydrogen gas (180 atm) with ionization and space-charge effects turned on only (scattering and straggling were not implemented).

The first simulation was without ionization effects turned on in order to have a baseline reference case. The second simulation added a plasma at each simulation step in the form of a thin cylinder of the beam radius containing the total number of plasma electrons (and ions) that were calculated to be created each step. The third simulation used a built-in ionization module of WARP that, given a cross section and density, would place an electron-ion pair at their creation point.

The number of secondaries generated in a single step can be calculated from the Bethe Equation [3] and is given by the following equation:

$$N_s = \left\langle \frac{dE}{dx} \right\rangle \frac{\rho}{W_i} \times d_s, \quad (1)$$

where N_s is the number of particles generated per step, d_s is the step length, $\left\langle \frac{dE}{dx} \right\rangle$ is the mean rate of energy loss by the muons, W_i is the average energy to produce an ion pair, and ρ is the mass density of the medium.

The cross section (σ) for a single particle in the beam is given by

$$R = nv\sigma, \quad (2)$$

where R is the rate of the reaction, v is the velocity of the beam, n is the number density of target particles. That leads to the cross section formula

$$\sigma = \left\langle \frac{dE}{dx} \right\rangle \frac{1}{W_i} \frac{\rho}{\rho_n}, \quad (3)$$

where ρ is the mass density of the absorber and ρ_n is the atomic density of the absorber.

QUALITATIVE RESULTS

From these simple simulations, it is seen that beam-plasma effects can significantly alter the simulation as seen in Table 1. The bunch shape varies drastically when comparing the simulation with and without plasma effects. These also show that simple results with manually added plasma are not as accurate as with WARP-generated plasma. WARP can calculate the desired effects fairly quickly. In these simulations, there was a factor of six slowdown when including plasma, which is not prohibitive.

The main result of the beam-plasma interaction is the effect of charge neutralization. Consider a bunch of positive muons ionizing a material. Due to space charge effects, they will tend to spread out. When the plasma is created, the plasma electrons are mobile, while the ions are not. The electrons are attracted to and move towards the center of the bunch, lowering the net charge and reducing the repelling space charge force felt by the muons. Overall then, the spread in the bunch tail is less than the spread in the bunch head. Compare the bunch tail in the simulations with plasma to the one without in Table 1.

PROGRESS IN QUANTITATIVE RESULTS

Beam-plasma effects have been shown to potentially have a significant effect on the shape of a muon bunch. This needs to be quantified, and an accurate effect on cooling rates needs to be studied. To do this, a complete cooling cell has to be simulated.

In the previous simulations, scattering and straggling have been neglected, due to a lack of these features in WARP. Recently, a WARP-ICOOL wrapper has been used [4], incorporating into WARP the scattering and straggling processes from ICOOL. At the end of each step inside material, WARP calls the relevant ICOOL processes and applies them to the particles in the simulation.

The first steps towards simulating a complete cooling cell in WARP have been made, using the first stage of the six-dimensional ionization cooling channel under development by the Muon Accelerator Program (MAP) [5]. A pre-calculated magnetic field map and hard-edged 325 MHz RF cavities have been inserted into the WARP simulation, and an identical lattice has been set up in ICOOL [6]. A successful attempt at comparing the two simulation results has been made for a small sample distribution. In the future, a simulation of the final stages of the cooling channel is

planned, where densities are much higher and beam-plasma effects should be more prominent.

CURRENT CHALLENGES

Although the results so far are promising, many challenges still exist. The plasma behavior needs to be honed to be more precise, depending on the material. In different materials, plasma electrons will have varying mobility, and as charge neutralization is the biggest cause of the beam-plasma effects seen, modeling the electron behavior more accurately is a priority. Also yet to be incorporated into the simulations is the process of secondary electron generation potentially ionizing more of the material themselves.

After the simulation is as accurate as possible, the results need to be validated. This would include comparing results to analytic calculations, applicable experiments, and other simulations.

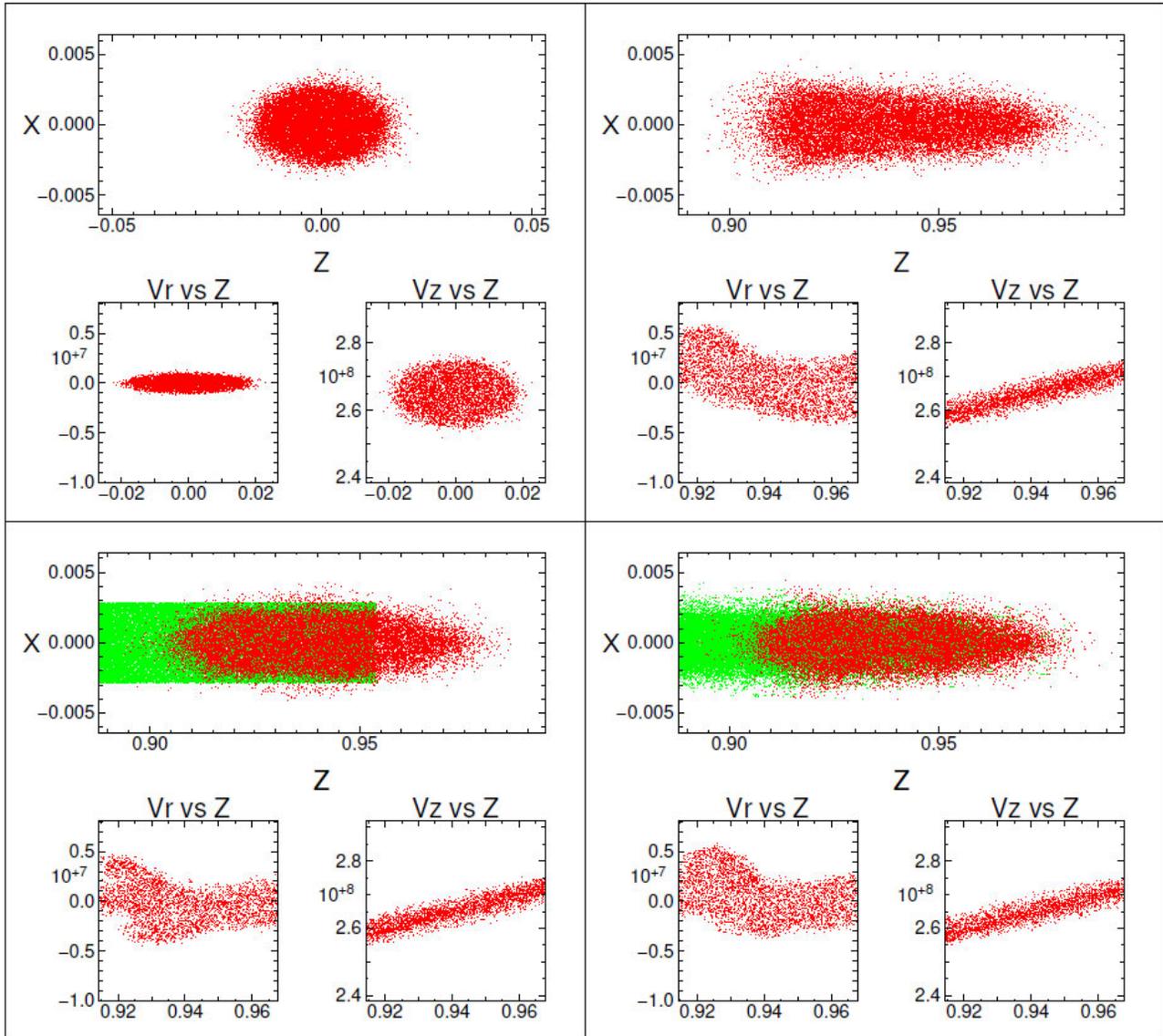
ACKNOWLEDGMENT

Authors would like to thank Alvin Tollestrup, Ben Freemire, and Katsuya Yonehara for many fruitful discussions, along with David Grote and Jean-Luc Vay for assistance with the WARP simulation package they (and others) developed.

REFERENCES

- [1] S. Ahmed, D. Kaplan, T. Roberts, L. Spentzouris, K. Beard, (2012) "Interaction Of Muon Beam With Plasma Developed During Ionization Cooling" *IPAC2012 TUEPPB001* <http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/tueppb001.pdf>
- [2] A. Friedman, R. H. Cohen, D. P. Grote, S. M. Lund, W. M. Sharp, J.-L. Vay, I. Haber, and R. A. Kishek, "Computational Methods in the Warp Code Framework for Kinetic Simulations of Particle Beams and Plasmas," *IEEE Trans. Plasma Sci.* vol. 42, no. 5, p. 1321 (May 2014); <http://dx.doi.org/10.1109/TPS.2014.2308546>
- [3] K.A. Olive *et al.*, (particle Data Group), *Chin. Phys. C* **38**, 090001 (2014)
- [4] David Grote and Jean-Luc Vay, personal correspondence
- [5] Muon Accelerator Program, <http://www.map.fnal.gov>
- [6] R.C. Fernow *et al.*, *ICOOL* (Version 3.23) <http://www.cap.bnl.gov/ICOOL/>

Table 1: Qualitative simulation results in three distributions: X vs Z , V_r vs Z , and V_z vs Z . All units are MKS. Muons are in red and plasma electrons are in green. (Top-left) The initial Gaussian distribution. (Top-right) A simulation without plasma effects after 3550 steps. (Bottom-left) A simulation with plasma added manually at each step. (Bottom-right) A simulation with plasma added by WARP at ionization locations. Note the tail of the bunch spreading less when plasma is involved due to charge neutralization, and edge effects appearing in the V_r vs Z distribution for the manually added plasma



Content from this work may be used under the terms of the CC BY 3.0 licence (© 2015). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.